

# DCT-like Transform for Image and Video Compression Requires 10 Additions Only

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## Abstract

A multiplierless pruned approximate 8-point discrete cosine transform (DCT) requiring only 10 additions is introduced. The proposed algorithm was assessed in image and video compression, showing competitive performance with state-of-the-art methods. Digital implementation in 45 nm CMOS technology up to place-and-route level indicates clock speed of 255 MHz at a 1.1V supply. The 8×8 block rate is 31.875 MHz. The DCT approximation was embedded into HEVC reference software; resulting video frames, at up to 327 Hz for 8-bit RGB HEVC, presented negligible image degradation.

**Index terms**— Approximate discrete cosine transform, pruning, HEVC

## 1 Introduction

The discrete cosine transform (DCT) plays a fundamental role in signal processing techniques [34] and is part of modern image and video standards, such as JPEG [42], MPEG-1 [36], MPEG-2 [18], H.261 [19], H.263 [20], H.264/AVC [40, 46], and the high efficiency video coding (HEVC) [21, 33]. In particular, the transform coding stage of the H.264 and HEVC standards employ the 8-point DCT of type II [33, 39] among other different blocklengths, such as 4, 16, and 32 points [5, 30, 31]. In [32], the 8-point DCT stage of the HECV was optimized. Among the above-mentioned standards, the HEVC is capable of achieving high compression performance at approximately half the bit rate required by H.264/AVC with same image quality [28, 30, 32, 33]. However, HEVC possesses a significant computational complexity in terms of arithmetic operations [28, 30, 32, 39]. In fact, HEVC can be 2–4 times more computationally demanding when compared to H.264/AVC [30, 32]. Therefore, the proposal of efficient low-complexity DCT-like approximations can benefit future video codecs including emerging HEVC systems.

Recently, low-complexity DCT approximations have been considered for image and video processing [4, 5, 7–9, 14–16, 32]. Such approximate transforms can reduce the computational demands of the DCT, leading to low-power, high-speed realizations [32], while ensuring adequate numerical accuracy.

In some applications, such as data compression [35], high-frequency components are often zeroed by the quantization process. Thus, one may judiciously restrict the computation of transform algorithms to the quantities that

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are likely to remain significant [17]. This approach is called *pruning* and was originally proposed as a method for computing the discrete Fourier transform (DFT) [26, 37]. In this context, pruning was done in time-domain, i.e., particular input samples are ignored and the operations involving them are avoided [3]. Frequency-domain pruning—discarding transform coefficients—is an alternative. The latter approach has been recently applied in mixed-radix FFT algorithms [43], cognitive radio design [2], and wireless communications [45]. Another example of a pruning-like algorithm is the well-known Goertzel method for DFT computation [11, 23, 29].

For the DCT case, pruning was originally proposed by Wang in [44] considering a decimation-in-time algorithm for power-of-two blocklengths. In [38], such algorithm was generalized for arbitrary blocklength. In [25], Lecuire *et al.* extended the pruning technique to the two-dimensional case, referring to the method as the zonal DCT, which is an alternative terminology. In the context of low-powered wireless vision sensor networks, a pruned approximate DCT was proposed in [24] based on the DCT approximation theory advanced in [9].

In [27], Meher *et al.* proposes an architecture for HEVC based on an integer DCT. Such architecture employs pruning, but in a different sense. In that work, the pruning operation is not performed in the terms of avoiding the computation of specific output transform coefficients. Instead, the pruning is referred to as the operation of discarding least significant bits of a given computation architecture to limit or reduce its computation complexity, at the expense of truncation errors [27]. In contrast, the present work addresses pruning in the sense of discarding transform coefficients. It is noteworthy to establish this distinction in terminology.

Thus, in response to the growing need for high compression of image and moving pictures for various applications as prescribed in [21], we propose a further reduction of the computational cost of the DCT computation in the context of JPEG-like compression and HEVC processing. In the present work, we introduce a multiplication-free pruned approximate 8-point DCT. We also provide VLSI realizations of both 1-D and 2-D versions of the proposed pruned approximate transform. Proposed methods are sought to be fully embedded into an open source HEVC reference software [22] for performance assessment in real time video coding.

## 2 Proposed pruned approximate DCT

### 2.1 Proposed approximation

In [4] a very low-complexity 8-point DCT approximation was introduced and it is referred to as the modified rounded DCT (RDCT). Its associated fast algorithm requires only 14 additions, having the lowest computational complexity among the meaningful DCT approximations archived in literature [4, 7–10, 14, 16, 32]. This particular approximation was successfully employed in HEVC as shown in [32].

By means of analyzing 50  $512 \times 512$  8-bit representative standard images [41], we noticed that the 2-D version of the modified RDCT [4] can concentrate in average  $\approx 98\%$  of the total image energy in the 16 lower frequency coefficients. Additionally, in JPEG-like image compression, the quantization step is prone to zero the high frequency coefficients [25]. Therefore, computational efforts may be saved by not computing the high frequency coefficients, keeping only low-frequency coefficients. These considerations yield to the following transformation derived from the

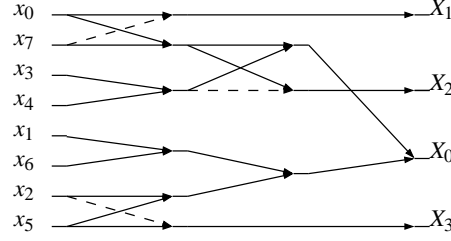


Figure 1: Signal flow graph relating input data  $x_n$ ,  $n = 0, 1, \dots, 7$ , to output  $X_k$ ,  $k = 0, 1, 3, 4$ , according to  $\mathbf{T}$ . Dashed arrows are multiplications by  $-1$ .

low-complexity matrix associated to the modified RDCT:

$$\mathbf{T} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & -1 & -1 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}.$$

Above transformation computes the four lower frequency components of the 1-D modified RDCT, which corresponds to the 16 lower frequency components of the associated 2-D version. Notice that the rows of  $\mathbf{T}$  form an orthogonal set. Thus, considering the orthogonalization methods described in [13], we can obtain a semi-orthogonal matrix given by:

$$\hat{\mathbf{C}} = \mathbf{D} \cdot \mathbf{T} = \text{diag} \left( \frac{1}{\sqrt{8}}, \frac{1}{\sqrt{2}}, \frac{1}{2}, \frac{1}{\sqrt{2}} \right) \cdot \mathbf{T}.$$

Matrix  $\hat{\mathbf{C}}$  is the pruned version of the modified RDCT. For image and video compression, the scaling diagonal matrix  $\mathbf{D}$  does not introduce any computational overhead, since it can be merged into the quantization step [4, 7, 8, 14, 32]. Fig. 1 provides the signal flow graph of the fast algorithm for  $\mathbf{T}$ , relating input signal  $x_n$ ,  $n = 0, 1, \dots, 7$  to output signal  $X_k$ ,  $k = 0, 1, \dots, 7$ . Transform-domain components  $X_4, \dots, X_7$  are not represented, being set to zero. The 2-D forward zonal transformation is mathematically described according to:

$$\mathbf{B} = \hat{\mathbf{C}} \cdot \mathbf{A} \cdot \hat{\mathbf{C}}^\top,$$

where  $\mathbf{A}$  is an input  $8 \times 8$  matrix,  $\mathbf{B}$  is the associated transform-domain  $4 \times 4$  matrix and superscript  $\top$  indicates matrix transposition.

## 2.2 Complexity Assessment

By counting the number of multiplications, additions, and bit-shifting operations, we assessed the computational cost of the proposed 1-D and 2-D pruned modified RDCT. Table 1 compares the obtained complexities with traditional and state-of-the-art DCT methods. Here, we included the computational cost of the DCT computation according to Chen's DCT algorithm [12], which is the algorithm employed in the HECV codec [22]. Each of the selected methods was assessed both in its full and pruned versions. The 1-D and 2-D versions retained the four and 16 lower frequency coefficients, respectively.

The proposed 1-D technique demands *only 10 additions*, which corresponds to 58.3%, 58.3%, 54.5%, 50.0%,

Table 1: Computational complexity assessment

Method	1-D						2-D					
	Nonpruned			Pruned			Nonpruned			Pruned		
	Mult.	Add.	Shift	Mult.	Add.	Shift	Mult.	Add.	Shift	Mult.	Add.	Shift
DCT (by definition)	64	56	0	32	28	0	1024	896	0	384	336	0
Chen's DCT [12]	16	26	0	6	12	0	256	416	0	72	144	0
SDCT [16]	0	24	0	0	20	0	0	384	0	0	240	0
BAS-2008 [7]	0	18	2	0	14	1	0	288	32	0	168	12
BAS-2009 [8]	0	18	0	0	14	0	0	288	0	0	168	0
BAS-2013 [9, 24]	0	24	0	0	20	0	0	384	0	0	240	0
RDCT [14]	0	22	0	0	16	0	0	352	0	0	192	0
Modified RDCT [4]	0	14	0	0	<b>10</b>	0	0	224	0	0	<b>120</b>	0

Table 2: Performance assessment

Method	Nonpruned		Pruned	
	PSNR	NZ (%)	PSNR	NZ (%)
Chen's DCT [12]	33.10	81.83	30.40	86.19
SDCT [16]	29.28	80.20	27.14	86.27
BAS-2008 [7]	32.17	80.87	29.24	86.00
BAS-2009 [8]	31.72	80.59	28.69	86.16
BAS-2013 [9, 24]	31.82	80.52	28.72	86.10
RDCT [14]	31.91	81.03	28.93	86.45
Modified RDCT [4]	30.94	79.83	26.37	<b>86.75</b>

44.4%, and 28.6% less operations than the SDCT [16], BAS-2013 [9], RDCT [14], BAS-2008 [7], BAS-2009 [8], and the original modified RDCT, respectively. When considering the 2-D transformation, arithmetic complexity reduction effected by the pruning procedure is even more significant.

In fact, the  $8 \times 8$  nonpruned 2-D transformation can be decomposed into eight nonpruned row-wise 1-D transformations; followed by eight column-wise instantiations of the same 1-D transformation. In contrast, the proposed pruned 2-D transformation can be decomposed into eight pruned row-wise 1-D transformations of the rows; followed by only four pruned 1-D transformations. Therefore, the pruned 2-D transformation calls the 1-D algorithm fewer times when compared with the nonpruned case. The complexity values presented in Table 1 were calculated according to above considerations. As a consequence, the proposed transformation requires *120 additions*, which corresponds to 68.8%, 68.8%, 65.9%, 62.5%, 58.3%, and 46.4% less operations than the above-mentioned algorithms, respectively, in their full nonpruned versions. Additionally, the proposed method outperforms the recently proposed zonal approximation described in [24], requiring 50% less operations for both 1-D and 2-D versions. Moreover, the comparison among pruned-only versions of above methods shows that the proposed approximation demands 28.5% less operations, in both 1-D and 2-D cases, than the best competing methods, namely BAS-2008 [7] and BAS-2009 [8].

### 3 Image compression

Considering the image compression simulation in [4, 7, 14], we employed same set of images mentioned in the previous section. Images were subdivided in  $8 \times 8$  blocks and were submitted to 2-D transformation according to the proposed

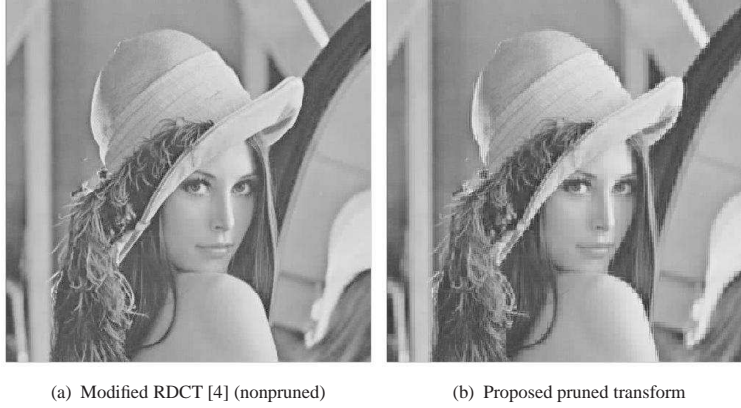


Figure 2: Compressed Lena images.

pruned approximate DCT and competing methods. The resulting coefficients in the transform domain were submitted to the standard quantization operation for luminance [6, p. 155]. Subsequently, full inverse transformations were applied and compressed images were obtained. Original and processed images were evaluated for image degradation using the peak signal-to-noise ratio (PSNR). We also computed the number of zeros (NZ) after quantization, which furnishes a measure of energy compaction in the transform domain. High values of NZ translates into longer runs of zeros, which are beneficial for subsequent run-length encoding and Huffman coding stages.

In contrast with [7–9, 24], we adopted average measurements, which are less prone to variance effects. Table 2 shows the average PSNR values and percent values for NZ based on the selected image set for each considered method. Results indicate that the proposed method can significantly reduce the computational complexity, while maintaining good PSNR figures. A qualitative comparison between the Lena [41] compressed image obtained from the above describe procedure using the modified RDCT [4] and the proposed pruned transform is shown in Fig. 2.

## 4 VLSI architectures

To further investigate the capabilities of the proposed algorithm, we separate the modified RDCT and the proposed pruned approximation for hardware implementation and evaluation in the actual HEVC scheme.

### 4.1 FPGA Architecture

These approximations were realized as a separable 2-D block transform using two 1-D transform blocks and a transpose buffer. Such blocks were initially modeled and tested in Matlab Simulink and then combined to furnish the complete 2-D transform. The resulting architecture was physically realized on a Xilinx Virtex-6 XC6VLX240T-1FFG1156 field programmable gate array (FPGA) device and validated using hardware-in-the-loop testing through the JTAG interface. The DCT approximation FPGA prototype was verified using more than 10000 test vectors with complete agreement with theoretical values.

Table 3: Resource consumption on Xilinx XC6VLX240T-1FFG1156 device.

Method	CLB	FF	CPD	$F_{\max}$	$D_p$	$Q_p$
Modified RDCT	381	1056	3.407	293.51	2.31	3.44
Proposed	266	650	2.77	361.01	1.11	3.437

Table 4: Resource consumption for CMOS 45 nm implementation.

Method	Area	AT	AT <sup>2</sup>	CPD	$F_{\max}$	$D_p$	$Q_p$
Modified RDCT	0.077	0.318	1.313	4.13	242.13	0.062	0.057
Proposed	0.043	0.167	0.657	3.92	255.10	0.033	0.034

## 4.2 CMOS Place-Route

Following FPGA based verification, the hardware description language code was ported to 45 nm CMOS technology and subject to synthesis and place-and-route steps using Cadence Encounter. Both FPGA implementation and CMOS place-and-route results are tabulated in Table 3 and 4, respectively. Metrics, including configurable logic blocks (CLB) and flip-flop (FF) count, critical path delay (CPD) (in ns), area (in mm<sup>2</sup>), area-time complexity (AT, in mm<sup>2</sup> · ns), area-time-squared complexity (AT<sup>2</sup>, in mm<sup>2</sup> · ns<sup>2</sup>), and maximum operating frequency ( $F_{\max}$ , in MHz), are provided. Quantities were obtained from the Xilinx FPGA synthesis and place-and-route tools by accessing the `xflow.results` report file for each run of the design flow. In addition, static ( $Q_p$ , in W) and frequency normalized dynamic power ( $D_p$ , in mW/MHz) consumptions were estimated using the Xilinx XPower Analyzer.

The FPGA realization of the proposed pruned DCT approximation showed a reduction of 46.16% in area as measured by the number of CLBs and a 50.17% reduction in frequency normalized dynamic power consumption when compared with the full DCT approximation. Synthesis at the 45 nm CMOS technology node using FreePDK45 standard cells revealed a 44.41% reduction in area and a 48.67% reduction in frequency normalised dynamic power for a supply voltage fixed at  $V_{DD} = 1.1$  V. All metrics indicate clear advantages of using the proposed pruned DCT approximation over the full 8-point approximation. Further, a 255 MHz CMOS clock indicates a block rate of 31.875 MHz, and a frame-rate of 327 Hz assuming 1080p 8-bit RGB video at 1920×1080 resolution.

## 5 HEVC software simulation

We considered real time video coding by embedding the proposed algorithms into the HEVC reference software by the Fraunhofer Heinrich Hertz Institute [22]. The original transform in the HEVC reference software is the scaled approximation of Chen’s DCT algorithm. Our methodology consists of replacing the 8×8 DCT algorithm of the reference software by the modified RDCT and the proposed pruned approximation.

Fig. 3 shows three 416×240 frames of the ‘BasketballPass’ test sequence [1] obtained from the HECV simulation. Resulting frames were coded using the Chen’s DCT algorithm (Fig. 3(a)), the modified RDCT (Fig. 3(b)), and the proposed pruned approximation (Fig. 3(c)). The PSNR values for these three frames were 37.62, 37.42, and 37.41 dB, respectively. Therefore, the pruned approximation effected minimal image degradation—less than 0.25 dB. The computational complexity of the 8-point DCT was significantly reduced—76.2% less arithmetic operations when compared with the original Chen’s DCT algorithm.



(a)



(b)



(c)

Figure 3: Selected frame from ‘BasketballPass’ test video coded by means of (a) the Chen’s DCT algorithm, (b) the modified RDCT, and (c) the proposed pruned approximation.



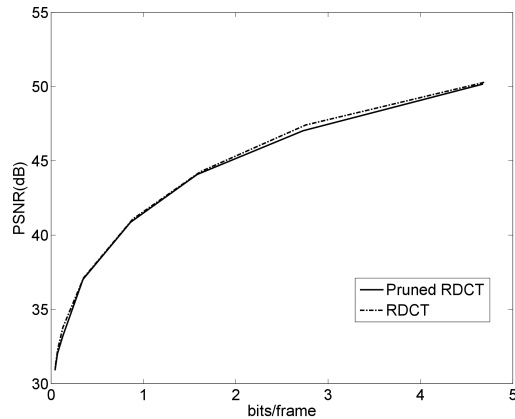


Figure 4: RD curves for ‘BasketballPass’ test sequence.

We have also computed rate distortion (RD) curves for both RDCT and the proposed pruned approximation using standard video sequences [1]. For such, we varied the quantization point (QP) from 0 to 50 and computed the PSNR of the proposed pruned approximate with reference to the RDCT along with the bits/frame of the encoded video. As a result, we obtained the curves shown in Fig. 4. The difference in the rate points between the RDCT and the proposed pruned approximation is less than 0.57dB, which is negligible.

## 6 Conclusion

In this paper, we presented a *very* low-complexity DCT approximation obtained via pruning. The resulting approximate transform requires *only* 10 additions and possesses performance metrics comparable with state-of-the-art methods, including the recent architecture presented in [24]. By means of computational simulation, VLSI hardware realizations, and a full HECV implementation, we demonstrated the practical relevance of our method as an image and video codec.

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